

Incorporating water into land system science: Jevons' paradox, Center Pivot Irrigation (CPI), and socioecological resilience in a transboundary area of the Southern Great Plains (SGP)

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ABSTRACT

The Southern Great Plains (SGP) is subject to cyclical drought and growing dependence on groundwater for irrigation. The drawdown of the Ogallala Aquifer threatens socioecological resilience of rural agricultural communities. Here, center pivot irrigation (CPI) has been introduced as a technological solution for efficient water consumption. We argue that Land System Science (LSS) needs to include more direct engagement with water as both a material and hydrosocially produced object integral to the study of land. Using Jevons' Paradox and the case of CPI growth in two counties/states between 2005 and 2020, we draw on a remote sensing analysis of irrigated and dryland agriculture, household surveys, and key informant interviews to triangulate results for more holistic understandings of land-water-people dynamics. Remote sensing results show large growth in CPI with a more recent slowing down of growth rates, while the proportion of irrigated to non-irrigated agriculture is increasing, raising questions of long-term water sustainability. The household survey results and key-informant interviews reveal a nuanced view of irrigation dynamics, illustrating tensions between residents' perceptions regarding water sustainability and the reality of their lived experiences. While ambiguity exists, most respondents perceive their situation to be more precarious as a result of irrigation (irrespective of the adoption and growth of CPI technologies). Moreover, decision-making is largely predicated on economic (rather than environmental) factors. The Jevons' Paradox framework illustrates that CPI appears to have the opposite effect of its original intentions, as the majority of residents feel that CPI makes them more vulnerable in the long run.

1. Introduction

Water scarcity affects land-use and land-cover changes (LULCC), impacting land management and socioecological resilience (Lambin and Geist, 2006; Vadjunec et al., 2018). Cyclical drought coupled with overuse of groundwater for irrigation threatens the sustainability of agricultural production, regional lifeways, and national and international food security (McGuire, 2017; McGuire and Strauch, 2014). We argue that engaging more deeply with water in Land System Science (LSS) will ensure sustainable stewardship of natural resources while reducing people's vulnerability and increasing socioecological resilience (Aspinall and Staiano, 2017; Boelens et al., 2016; Earth System Governance Project, 2018; Ricart and Kirk, 2022).

The Ogallala Aquifer region is the epicenter of the historic "Dust

Bowl" which battered the region in the 1930s (Duncan and Burns, 2012; Egan, 2006), only to later (re)emerge as the agricultural "breadbasket" of the US (Debaere, 2017) and the world (Sanderson and Frey, 2015). Center Pivot Irrigation (CPI), introduced in the 1950s, was intended to help "drought-proof" agricultural operations while increasing efficient water use (Wenger et al., 2017). However, withdrawals from the Ogallala Aquifer exceed recharge rates, calling into question the future sustainability of irrigated agricultural production and livelihoods in the region and beyond. Using a case study from the Southern Great Plains (SGP)/Ogallala Aquifer, we explore the economic, social, spatial, and material effects of technological intervention as a strategy for drought mitigation. We interrogate technological efficiency as a solution to resource scarcity by applying Jevons' Paradox: "in the long term, an increase in efficiency in resource use will generate an increase in

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resource consumption rather than a decrease” (Giampietro and Mayumi, 2018). We suggest that the SGP illustrates that the introduction and proliferation of CPI creates an illusion of water sustainability and socioecological resilience. The logic of technological efficiency increases water consumption, effectively *intensifying* the depletion of the Ogallala Aquifer.

Using a mixed methods approach, we ask:

- 1) How has (irrigated) agriculture changed over time and space (2005–2020)?
- 2) How does CPI impact perceptions of socioecological resilience & vulnerability across (household and community) scales?

First, we discuss the importance of including water in LSS followed by a discussion of ecological modernization theory and Jevons’ Paradox. Next, we provide background regarding the study area, followed by a discussion of our mixed-methods approach. After presenting and discussing our results, we provide concluding remarks about the relationship between CPI growth, water sustainability, and socioecological resilience.

1.1. Water in Land System Science (LSS)

Global LSS research highlights the extent and drivers of anthropogenic alterations on Earth (Verburg et al., 2013). Agricultural development, a primary driver of land-use and land-cover change (LULCC), contributes to changes in natural systems, including climatic, atmospheric, hydrological, terrestrial, and biodiversity (Geist and Lambin, 2002; Pielke Sr et al., 2016). These natural systems changes are interconnected with human systems impacting society, livelihood, vulnerability, and resilience, and vice versa (Vadjunec et al., 2022). Modelling the complex processes and impacts of LULCC by studying the interaction between humans and their environment drives the development of LSS (Turner, 2010). As such, a holistic consideration of multi-scalar and temporal interactions of complex socioecological systems (SES) is key to develop critical understandings of the human-environment condition (Rounsevell et al., 2012; Brannstrom and Vadjunec, 2013; Vadjunec et al., 2018) LSS employs diverse spatial methodologies (e.g. geographic information systems (GIS) and remote sensing) with mixed methods to measure, model, and predict complex LULCC dynamics, with an eye toward socializing the pixel (NRC, 1998; Turner et al., 2007).

Trade-offs and interaction effects between and across multiple spatial and temporal scales are common in LSS (Frazier et al., 2019). However, the interscalar interactions and subsequent impacts can get “lost” in more traditional static macro-level analytic frameworks. For instance, federal level policy aimed to conserve resources and/or increase economic production shapes regional and micro-level processes and decisions related to resource consumption. Conversely, studying decision-making processes and resource consumption at finer scales is also necessary to inform how policy is (re)formulated at regional or national scales—especially when considering shared resources such as public land or water (Bottazzi and Dao, 2013). Further, these complex interactions across and within scales are also multi-temporal as well, as some resources may be depleted more quickly, while others may take longer to develop due to temporal lags (Vadjunec et al., 2022).

Of particular importance to global sustainability issues (and the present study), water in LSS is often neglected. When water is considered, it is often abstract or implicit, generally in relation to a specific crop, or as a secondary, related impact or driver. We argue that this is often due to practical limitations of remote sensing. This is particularly

true of ground water, which remains invisible to such methods. Many of these frameworks focus primarily on terrestrial changes over time—often neglecting the more fluid and transient nature of water, not to mention the larger hydrologic systems which undergird terrestrial landscapes. As such, water is considered a commons, making it susceptible to degradation and overuse (Hardin, 1968). Tradeoffs and competition between food-energy-water (FEW) resources, various corporate, non-corporate, and governmental actors puts pressure on the quantity, quality, consumption and production of water across various spatial and temporal scales (Cansino-Loeza et al., 2020; D’Odorico et al., 2018; Riebsame, 1991; Riebsame, 1990). Increasingly, the impacts of climate change and unsustainable water use and degradation jeopardizes water and food security (DeFries and Eshleman, 2004; Vörösmarty et al., 2000). Formal and informal co-management is, therefore, crucial to ensure long-term sustainability (Ostrom, 1990). To accomplish this LSS research needs to include more direct engagement with water and/or hydrologic systems as both a material and hydrosocially produced object integral to land (DeFries and Eshleman, 2004; Marsh, 2023; Vadjunec et al., 2024).

Understanding the drivers of water degradation and overuse often requires institutional analysis including those operating at different spatial and temporal scales (e.g. legal geographies) from more traditional LULCC categories (Daniell and Barreteau, 2014). Further, understandings of water (especially groundwater) use and degradation is subject to lag effects (Hocking and Kelly, 2016). Lastly, water management policies are generally developed based on long-term sustainability goals (40+ years) which are often in direct conflict with short-term consumption patterns, wants, and needs (Cumming et al., 2006). These distinct characteristics of water, among others, make water’s inclusion in LSS studies and models more difficult (Daniell and Barreteau, 2014; Kugler et al., 2019). This paper navigates water complexities in LSS by deeply engaging with social theory while using mixed methods to triangulate data for more holistic understandings of land-water-people dynamics (Gomes et al., 2012; Vadjunec et al., 2018).

1.2. Ecological modernization and its critics: Jevons’ Paradox

The human response to resource scarcity has typically included technological development to improve efficiency (Beck, 1999; Beck, 1992). Ecological Modernization (EM) is a paradigmatic framework predicated on rationalism and modernity to understand and address environmental degradation, resource depletion, and scarcity (Spaargaren and Mol, 1992). Rather than fundamentally changing environmental relations, EM advocates for reform, “the only possible way out of the ecological crisis is by going further into the process of modernization” (Mol, 1996, p. 305; Spaargaren and Mol, 1992, p. 336). Further, and critical to the present study, EM logic asserts that reform simultaneously enhances economic production while improving environmental quality (Carolan, 2004; Mol and Spaargaren, 2004). First, state policy incentivizes producers to attenuate environmental degradation while creating new, sustainable economic trajectories. Second, technical experts and scientists collaborate with industry to develop technologies to make production less resource intensive (Mol, 1995; Spaargaren and Mol, 1992). The convergence of pro-environmental governance, scientific acumen, and industry capital makes production and consumptive practices more efficient—requiring fewer material inputs, reducing waste, and repairing damage done to the environment while bolstering economic growth (Mol et al., 2013). Fuel-efficient cars, the paperless office, and renewable energy technologies are examples of this process (York and McGee, 2016; Korhonen, 2008). Consequently,

EM grew in popularity among the academic community, drawing significant financial contributions from industry and governmental sources becoming the primary economic philosophy to confront environmental problems (Foster, 2012).

EM philosophy positions resource efficiency as the linchpin by which society will dematerialize the economy and usher in an environmentally sustainable future (Fisher and Freudenburg, 2001). The problem with using efficiency as a key predictor of eco-technical progress is that efficiency only considers economic output per unit of resource needed for production rather than measuring environmental impacts (York et al., 2010). These ratios can be intentionally misleading, as, for instance, when the George W. Bush administration created a new measure of carbon dioxide emission intensity. Rather than considering total emissions, they articulated emissions as a ratio to economic growth. Because increases in economic production outpaced the growth of emissions, the messaging positioned these data to show a net reduction in emissions rather than an overall increase, mischaracterizing US contributions to the climate change problem (Lynch et al., 2010).

1.3. Jevons' Paradox and the "rebound effect"

William Stanley Jevons, wrote *The Coal Question* (1865) to address Britain's concern about industrial coal consumption. Jevons (1865), p. 137) predicted that "the amount of useful work got out of coal may be made to increase manifold, while the amount of coal consumed is stationary or diminishing." Instead, Jevons found that increases in energy efficiency led to *increasing* levels of consumption. His study developed the "curse of energy efficiency," also known as Jevons' Paradox, or the "rebound effect" (Dumont et al., 2013; Foster et al., 2010; Jevons, 1865). This paradox occurs when the very solution to the problem of inefficiency creates a decrease in production costs facilitating further industrial expansion as well as increasing demand. Both contribute to an increase in resource consumption. As Jevons explained "to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth... *It is the very economy of its use which leads to its extensive consumption*" (emphasis added, (Jevons, 1865, pp. 137–141)).

However useful this phenomenon is in offering a critical analysis of modernization, technological innovation, and the economics of energy use, Jevons' paradox has limitations. Jevons fails to account for the ecological implications of an ever expanding and increasing demand for energy consumption. While the natural system is resilient, once resource withdrawals exceed that system's ability to recover, environmental degradation will occur (Foster et al., 2010; Marx, 1973). Here, limitless economic growth derived from resource extraction and consumption is incompatible with a natural system with material limits (Foster et al., 2010, p. 20; Marx, 1973; O'Connor, 1991).

Contemporary scholarship embraces a more holistic approach to test Jevons' concept while also extending its application to other resources, including water (Dumont et al., 2013). Dumont et al. (2013) use this concept to study water sustainability in Spain. Their findings attend to water quality, energy requirements for its extraction and distribution, and quality of life—still fall short of escaping economic reductionism of Jevons' original work (Dumont et al., 2013). Ultimately, focusing specifically on economic implications of technological innovation suggests prioritizing (rural) economic development before environmentalism (Obach, 2004). This approach ignores the entangled, interdependent ecological relationship between society and nature and positions them instead, in opposition to one another (Catton and Dunlap, 1978). Moreover, an exclusive emphasis on the material relationship between technological efficiency, economic production, and natural resource

consumption fails to properly account for human decision-making processes on water consumption.

More recently, political-economic theorists have begun to diverge from the assumption that increased technological efficiency has a direct, causal link to energy consumption (Freudenburg, 1985; Freudenburg and Gramling, 1994; Freudenburg and Gramling, 1993; Murphy and Dunlap, 2012; York and McGee, 2016). Other social factors—including market dynamics, political regulation, cultural milieus, and the development of alternative energy sources—create indirect effects that influence energy consumption practices. York and McGee (2016) refer to this nexus as developmental pathways—a holistic consideration of the historical trajectory and development of economic industry, the influence of culture on resource consumption, and the (lack of) diversity of industrial sectors (Freudenburg, 1985). This "developmental channelization" suggests that cultural, economic, and technological decisions made about development in the past create a contemporary dependence on those developmental outcomes (Freudenburg and Gramling, 1994; Freudenburg and Gramling, 1993; Gramling and Freudenburg, 1996). Developmental channelization makes continuity in future investment initiatives more likely due to the presence of industry specific infrastructure, logistical networks, and dominant local markets (Freudenburg, 1985; Freudenburg and Gramling, 1994). Investment in those industries increases over time creating an inertial force, making deviation from historical industrial trajectories increasingly difficult (Molotch et al., 2000; Murphy and Dunlap, 2012).

Sustainability scholarship tests path dependence, developmental channelization, and rolling inertia via quantitative analysis and experimental modelling methodologies. This work has become increasingly important in the study of water scarcity, particularly in spaces where arid climates coincide with limited economic opportunity outside agricultural production. Here, an economic reliance on finite groundwater sources places paramount importance on efficient water use to balance short-term agricultural yields with long-term conservation and sustainable economic growth—all within the context of an increasing population, global water scarcity, and climate change (Pfeiffer and Lin, 2014).

Many studies have concluded that technological developments designed to increase efficiency of water resources have not reduced water consumption as presumed by EM advocates. Instead, they observe the opposite effect (Huffaker and Whittlesey, 2003; Khanna and Anton, 2002; Peterson and Ding, 2005; Scheierling et al., 2006; Ward and Pulido-Velazquez, 2008). While these contemporary studies broaden their theoretical and methodological gaze to factors beyond material economics to include environmental, climatic, and agricultural dynamics, they mirror the limitations of previous empirical approaches as they fail to account for the contingencies of human and cultural dimensions (Sears et al., 2018). This obscures the contingent nature of social dynamics that factor heavily into decision-making processes about water consumption practices. We argue that scholarly attention should also focus on qualitative indicators such as policy incentives (e. g., Environmental Quality Incentives Program (EQIP), Conservation Reserve Program (CRP), biofuel subsidies, crop insurance, etc.), and other crucial social factors (corporatization of agriculture and absentee land ownership, risk perceptions about market volatility and environmental vulnerabilities) in order to broaden the narrow views of economic materialism and glean a robust, holistic perspective on water consumption (Pfeiffer and Lin, 2014).

2. Background

2.1. The United States High Plains/ Ogallala Aquifer

The Southern Great Plains (SGP) is a semi-arid, grassland dominated region in portions of Colorado, Kansas, New Mexico, Oklahoma and Texas and largely underlain by the Ogallala Aquifer. Characterized by moisture deficits and cyclical, recurrent drought (Worster, 2004), the SGP has experienced numerous extreme climate events, including the infamous 1930s “Dust Bowl”. The region, though, saw a precipitous rise in groundwater use after the 1950s “Little Dust Bowl,” fueled by a belief in plentiful groundwater, cheap fuel (Opie, 1993), and a desire to counter the devastating effects of regular cyclical drought (Carrasco Galvan et al., 2024). The resulting expansion of Center Pivot Irrigation (CPI) in the 1970s sprung from the need to ease agricultural producer vulnerability to drought in the region, while increasing water efficiency. Such technologies aided the shift to a corporatization model of agricultural efficiency. In the 1980s, the United States government began to subsidize the adoption of CPI, specifically, through the Environmental Quality Incentives Program (EQIP) facilitating investment in what was seen as an overall efficient irrigation technology (Wenger et al., 2017). However, even “efficient” irrigated agriculture, can compound the effects of drought, increasing socioecological vulnerability for some communities (Allen et al., 2007; Hornbeck and Keskin, 2014). While these technologies helped “drought proof” agriculture operations, adverse ecological effects also followed (McDermid et al., 2023), contributing to a “nationwide groundwater crisis” (Searcey and Erdesanaa, 2023).

Long-term climatological data suggests each ensuing drought has been more protracted and severe than the last, providing increasingly challenging conditions for local communities that depend on water for their economy and livelihoods (Allen et al., 2007; Fernando et al., 2016; Flanagan et al., 2017). Many climate change models suggest the SGP will experience among the worst economic repercussions in the United States (Hsiang et al., 2017). Dependency on the Ogallala—economically, politically, socially, and ecologically—is a cause for concern, especially where historically 99 % of groundwater withdrawals are dedicated to

Table 1

Demographic, physiographic, and agricultural characteristics of Cimarron County, OK and Union County, NM.

	Cimarron County, OK	Union County, NM
Area (km ²)	4768	9922
Population (2023)	2191	3964
Population Density per km ²	0.46	0.40
HPA Area (km ²)	3783	4029
Percent HPA	79.34	40.61
Groundwater Policy	Private Property/ Prior Appropriation	Public Resource/ Beneficial Use

agricultural production (Miller and Appel, 1997). For instance, there has been a sevenfold increase in water usage from the 1940s to the 1980s (McGuire and Strauch, 2014). The water table has dropped more than 150 ft in parts of Texas and Kansas (Sears et al., 2018). Scanlon et al. (2012) estimate that 35 % of the SPG will be unable to sustain irrigation within the next thirty years.

2.2. Diverse water governance and CPI growth in two counties

Our study area comprises two adjacent counties in the SGP, Cimarron County (CC), Oklahoma and Union County (UC), New Mexico (Fig. 1). The counties have a common socioecological background, with shared “frontier” histories, agriculture-based economies, and similar biophysical environments linked to recurrent, cyclical drought (Duncan and Burns, 2012; Egan, 2006). While the counties vary in size and overall population, they have similar population densities. Both counties have agriculture-based economies, and access to the same federal agricultural and environmental subsidies that drive technocratic solutions to water scarcity. Further, the Ogallala Aquifer underlies portions of each county, linking land managers’ decision-making ability to irrigate crops and influencing the nature of agriculture production (Table 1).

Groundwater governance varies by state (Vadajunec et al., 2018; Wenger et al., 2017). In CC, groundwater is private property and governed under prior appropriation. In UC, groundwater is regarded as public property, governed under prior appropriation, but allocated

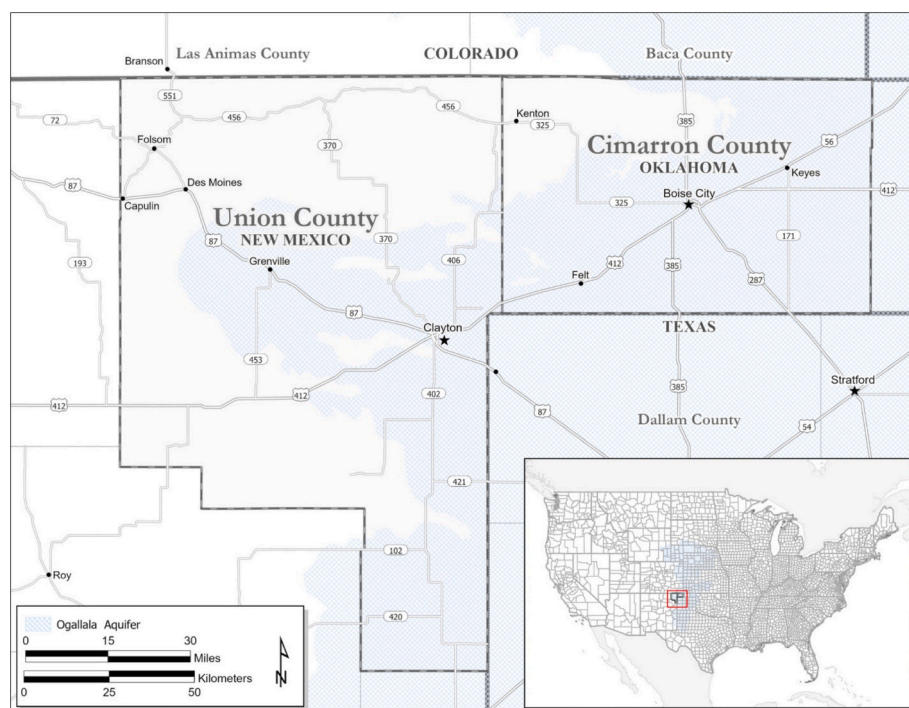


Fig. 1. Study area and Ogallala Aquifer.

based on jurisdiction by the state for beneficial use. The State Engineer in UC has ultimate permitting authority over all groundwater basins. In 2005, the NM State Engineer ended unrestricted groundwater appropriation in Union County and the Clayton Water Basin, while in OK, CC is perceived by many as relatively “wide open.” Overall, Ogallala water management practices (and resulting agricultural practices) differ across the two states. Research has demonstrated that differential policies regarding water use serve as drivers of LULCC dynamics in the region and influence the socioecological resilience of the system, especially during drought (Carrasco Galvan et al., 2024; Vadjunec et al., 2022).

Research illustrate that perceptions regarding the fairness of policies and land and water use across stateliness impact people’s decision-making processes (Wenger et al., 2017). Ultimately, policies that subsidize and/or regulate water use and consumption at state and county levels combine with federal policy to shape LULCC decision-making processes by the counties’ communities and households on the ground. These decisions, in turn, alter policy and decision-making processes at extra-local levels. The confluence of multi-scalar environmental and economic policy, biophysical dimensions of water availability and scarcity, and human-ecological dimensions of culture and agricultural livelihoods make this study site valuable for a holistic consideration of water conservancy, consumption, and the efficacy of technocratic solutions.

3. Methods

This research represents one aspect (i.e. irrigation) of a 15-year, ethnographic, field-based, mixed and participatory methods project looking at the long-term socioecological resilience of agricultural communities in the SGP. The current study builds on this past research but focuses on the most recent period of abnormally dry conditions with attention to illustrating how water-conserving technologies may have inadvertently led to increased use of groundwater resources. This research uses a mixed methods approach to triangulate results across scales.

3.1. Remote sensing analysis 2005–2020

To understand how (irrigated) agriculture changed over time and space (2005–2020, Q1), we acquired National Agriculture Imagery Program (NAIP) imagery for each of the two counties over four time periods: 2005–06; 2009–10; 2015–16; and 2019–20 (Table 2). We refer to this time series as 2005, 2010, 2015, and 2020, respectively. We used standard photogrammetric techniques to visually analyze each of the images at a scale of 1:24,000 to identify active agricultural activity. Beginning in the earliest image year for each county, we identified croplands using a heads-up digitizing approach and classified each field according to a three-tiered typology: center pivot irrigation (CPI); other irrigation (such as piped or flood); and traditional (dryland) agriculture. We then used the previous year’s features to inform the proceeding image years digitization. This ensured that fields that remained constant from one year to the next were identical in each layer. We then added, removed, or edited agriculture fields that emerged, were removed from production, or that otherwise changed, respectively, from image year to image year. This analysis was part of a larger land LULCC classification, but we only focus on the agricultural typologies here.

We defined CPI as irrigated agriculture in which irrigation equipment rotates around a pivot, irrigating a semi-/circular area on the

landscape. Most of the CPI in the study area utilizes groundwater resources, specifically the Ogallala, though some may utilize surface water resources. The circular fields characterized by CPI are easily identifiable on aerial and satellite imagery (Fig. 2a) and were primarily digitized using a circular trace tool (though additional editing was required for those fields that overlapped or were only half or quarter circles).

Digitizing other irrigation and traditional fields required visually differentiating agricultural activity from other LULCC types. This involved identifying specific shape, size, textures, patterns, and spectral tones characteristic of agricultural activity (Fig. 2b). Many of the agricultural fields in the area are rectilinear in shape, show evidence of row cropping and/or recent tillage, and tend to vary spectrally from non-agricultural areas. However, formerly cultivated “old fields” maintain some of the same spatial and spectral characteristics of active cultivation. Delineation was, therefore, often difficult. Once identified, we traced the boundaries of the agriculture fields and then classified as other irrigation or traditional (non-irrigated). Per the former, we used two primary criteria: Irrigation pipes visually present on the imagery and/or proximity to major surface water sources. We recognize some inherent subjectivity in the delineation of the latter, as some producers may forgo irrigation despite access to water resources. However, based on our groundwork, we know many producers will utilize water resources when accessible/available. The spectral characteristics of the fields also help in this delineation. Lastly, all dryland agriculture was classified as “traditional agriculture.”

We developed an accuracy assessment (AA) protocol using the most recent classified dataset to identify errors of omission (areas that should have been classified but were not) and errors of commission (areas that were incorrectly classified). First, over several field trips, we collected extensive ground truth data, including land cover type and coordinates. Second, we generated 1000 random XY points throughout the study area (500 per county) for all land cover classes to ensure no areas were improperly labeled as either one of our agriculture typologies or omitted altogether. Lastly, we created 300 random points within areas we classified as CPI (150 per county) to ensure all areas were properly classified. Every ground truth point was checked against our classification, while the random points were checked using high resolution imagery. We constructed a confusion matrix to assess the user and producer accuracy for each class and overall accuracy of the classification.

The AA demonstrates that our overall classification methodology is sound (96.73 %). At the individual county level, we had an overall accuracy of 98.4 % (CC) and 95.19 % (UC). The few classification errors resulted from incorrectly distinguishing herbaceous vegetation and traditional dryland agriculture. When we repeated the AA solely on areas classified as CPI, we had an increased accuracy of 99.67 %. We discovered an error of commission in CC, upon correcting this error, all pivots and non-pivots assessed in our AA were correctly identified.

We quantified changes in agriculture using three separate approaches (see Appendix 1): overall (raw) change from year to year; cumulative growth of CPI; and stability of CPI once brought into production. First, given that some fields were temporarily or permanently taken out of production or new fields were added to production year over year, we generated summary statistics for each year under investigation, both at the county and study area-wide level. However, we also recognize that this does not adequately capture the dynamics occurring because once a field is under an agricultural regime, there can be long lasting effects, even after the field is removed from production (Al-Busaidi et al., 2022). Second, rather than looking at absolute change over time, we quantified cumulative CPI growth from image year to image year. For instance, if there were 10 CPI fields in year 1 and 2 additional pivots were brought into production in year 2, the cumulative growth of pivots was 12, even if one or more fields were taken out of production in the period between the image dates. In this manner, we were able to quantify the total area under CPI over our study period. Lastly, we created a basic typology to identify wells, that once brought into production, remained in production from year to year (defined as

Table 2
National Agriculture Imagery Program (NAIP imagery used for Cimarron County, OK and Union County, NM.

	2005–06	2009–10	2015–16	2019–20
Cimarron County, OK	2005	2010	2015	2019
Union County, NM	2006	2009	2016	2020



Fig. 2. NAIP aerial imagery examples showing the characteristic circle agriculture fields of center pivot agriculture and traditional rectilinear fields (A) and flood plain agriculture fields along a tributary of the Cimarron River (B). Both images captured at a scale of 1:24,000.

“stable wells”) and those that came in and out of production between years based on 2005 and 2010 data (defined as “unstable wells”). This distinction is important because the addition of a CPI is related to the installation of the entire CPI unit, which also consists of a well. As such, the related land use is one way of representing the materiality of the seemingly invisible ground water itself. At the same time, recognizing that well water pressures diminish with drawdown and use, CPIs might be taken out of use during extreme heat/drought, or due to the prices of certain crops, or when water production from wells might be combined as water pressure drops (Foster et al., 2015). Consequently, we also calculated “unstable” CPI, which is CPI that consists of a permanent well, but that goes in and out of production throughout the time series.

3.2. Environmental perceptions from household surveys and key-informant interviews

To explore how CPI impacts perception of socioecological resilience and vulnerability across (household and community) scales (Q2), we drew on household surveys data ($n = 70$) and key-informant (KI) interviews ($n = 47$; see Appendix 2 for summary of the specific questions used in this paper). The household survey is part of the larger, long-term project starting in 2009. The household survey was developed by the first author and first field tested (revised and retested) in 2012 using a randomly generated X,Y geographic coordinate selection process connecting landowners to land parcels via platts. A version of this same field-tested study has been subsequently used in multiple projects in the region. For this paper specifically, we draw on questions from the 2022 surveys as they best match the timeline of the key informant interviews. Household surveys were completed in summer of 2022 with the self-identified male and female (both, when possible) heads of household. For this particular project, households self-selected as part of the participatory aspects of the larger project, as such care should be taken with generalizability. However, as our project is predominantly geospatial, the counties and household selection were geographically stratified by quadrants during the recruitment phase to ensure geospatial representation across diverse terrain and the consequent accompanying agricultural type and livelihood trajectories. Surveys lasted ~60–90 min and included several hundred variables centered around the following sections: basic household demographic and land use information, farm and ranch management systems, agricultural production, water use, sustainability, drought perceptions, and household adaptations. In order to better triangulate mixed methods data streams, we provide simple, general statistics to better match “people to pixels” (NRC, 1998) on the ground in the communities.

To explore community and regional perspectives on sustainability and livelihood issues in the broader study area, anonymous KI interviews were completed in 2019 with high-level local, county, and regionally representative state government officials familiar with the area, and local leaders such as pastors, business advocacy groups, cattle and agricultural associations, natural resource management office staff, etc. KIs lasted ~60 min using a semi-structured format which standardized a specific set of questions, but also allowing the team to

capitalize on the KIs expertise. Extensive notes were taken during the KIs, producing over 300 pages of interview notes which were then coded using NVIVO software. This paper draws on the answers to one specific KI question and probe “in your opinion, does irrigation make the community more or less vulnerable to long-term drought? (Probe why or why not, how, etc.). Answers to this question were coded as more vulnerable, less vulnerable, and two more codes, “neutral” and “it’s complicated” later emerged. Additional subcodes using grounded theory techniques were used to more deeply explore the primary codes (Hay, 2000).

While the primary analysis of this paper is the county level mapping of the evolution of CPI data in the region, here we use the household and KI data to triangulate our data streams through synthesis to offer more robust understandings into the relationship of residents’ perceptions of household and community vulnerability and the growth of CPI in the

Table 3

Area (ha) and percentage of total agriculture lands (in parentheses) by year and county.

	Total Study Area			
	2005	2010	2015	2020
Center Pivot	54,211 (16.96)	56,211 (18.75)	58,800 (19.99)	59,066 (20.84)
Other Irrigation	1289 (0.4)	989 (0.33)	849 (0.29)	919 (0.32)
Traditional	264,162 (82.64)	242,636 (80.92)	234,358 (79.71)	223,433 (78.84)
Total	319,662 (100)	299,836 (100)	294,007 (100)	283,418 (100)
	Cimarron Co, OK			
	2005	2010	2015	2020
Center Pivot	31,618 (13.84)	33,207 (15.15)	35,993 (16.72)	36,051 (17.05)
Other Irrigation	181 (0.08)	189 (0.09)	75 (0.03)	77 (0.04)
Traditional	196,727 (86.09)	185,752 (84.76)	179,225 (83.25)	175,270 (82.92)
Total	228,526 (100)	219,148 (100)	215,293 (100)	211,381 (100)
	Union Co, NM			
	2005	2010	2015	2020
Center Pivot	22,593 (24.79)	23,004 (28.51)	22,807 (28.97)	23,015 (31.96)
Other Irrigation	1108 (1.22)	800 (0.99)	774 (0.98)	842 (1.17)
Traditional	67,435 (73.99)	56,884 (70.50)	55,133 (70.04)	48,163 (66.87)
Total	91,136 (100)	80,688 (100)	78,714 (100)	72,020 (100)

region. Together, ethnographic data helps to illustrate the nuances of the remote sensing analysis across household (survey) and community (KI interview) scales. To protect human subjects on a highly controversial topic in very rural counties where everyone knows everyone, we pull the key informant interviews and surveys together across counties to further ensure anonymity, while focusing on triangulation of results and big picture trends from the study area.

4. Results

4.1. Overall change: traditional and irrigated agriculture, 2005–2020

Throughout the time period, the study site saw a steady increase in the area under CPI (+8.96 %) with a concurrent, but disproportionate decrease in both traditional dryland (−15.42 %) and other irrigated agriculture (−28.7 %). Traditional agriculture was the dominant (per area) agricultural practice in the region throughout the period comprising ~80 % of all agricultural lands each year. Conversely, CPI comprised only a relatively small proportion of all agriculture lands throughout the study period. However, this value steadily increased from ~17 % in 2005 to 21 % in 2020. Despite the growth of CPI, the total area classified as agricultural lands decreased each year with a total decrease of ~11.34 % from 2005 to 2020 (Table 3). These results indicate that, while agricultural practices were overall reduced during a period of prolonged drought, that the ostensibly water conserving technologies of CPI expanded to ensure continued production during drier than normal conditions.

4.2. Raw changes in CPI and other agriculture types at the county level, 2005–2020

Similar trends are seen at the individual county level. CC, with large portions of the county underlain by the Ogallala Aquifer (see Fig. 3), had the bulk of CPI during the period under investigation and saw steady increase in CPI between each period (see Table 3) with a 14.02 % overall increase from 2005 to 2020. As with the study area as a whole, CPI only comprised a small, but growing proportion of total agricultural lands in CC, ~14 % thereof in 2005 and 17 % thereof by 2020. Other irrigation, while mostly negligible in CC, slightly increased from 2005 to 2010, then decreased from 2010 to 2015, and slightly increasing again in

2020. Traditional dryland agriculture was the largest cultivated category in CC, comprising 84 % of all cultivated lands in CC during the period of investigation. However, as CPI increased, the area under traditional agriculture in CC also decreased by 10.91 % from 2005 to 2010 (see Table 3). From previous work in the region, this may in part be due to external crop price fluctuations vs. costs of production. For instance, in non-drought years many producers will use CPI to grow corn (a water heavy crop) once the price gets above \$2.50 a bushel. In the same vein, in particularly drouthy years or during market fluctuations, some producers will abandon CPI all together and go back to dryland agriculture as it can be perceived as less risky (see Carrasco Galvan et al., 2024).

Whereas CC saw relatively large increases in CPI over the study period, CPI remained relatively steady in UC during the period of investigation. UC, though covering a larger area, is only partially underlain by the HPA (see Fig. 1). Nonetheless, CPI is important to agriculture in the county, primarily in the eastern portion. However, New Mexico also has more restrictive ground water governance (above). Specifically, in 2005, the NM State Engineer ended unrestricted groundwater appropriation in Union County and the Clayton Water Basin. Further, the county has a long running participatory groundwater monitoring program through the local Soil and Water Conservation District (SWCD) which monitors withdraw and recharge rates to encourage better land management practices and educated decision making (Wenger et al., 2017). This is reflected in the agricultural dynamics of UC, which only saw only a modest increase (1.87 %) of CPI over the same fifteen-year period (Table 3). Moreover, unlike CC, which saw a steady increase in CPI over time, UC witnessed an oscillation in CPI acreage, increasing, then decreasing, only to slightly increase again. Concurrently, both other irrigation and traditional agriculture decreased over the entire period (see Fig. 3). Similar to both the results from both the study area (as a whole) and CC, traditional dryland agriculture was the dominant form of agriculture in UC, comprising ~70 % of all agricultural lands during the same period. However, as overall agriculture decreases and CPI growth rates appear to taper off or stabilize, CPI becomes an increasingly larger share of the total agriculture in general in the study area increasing from ~25 % of all agricultural lands in UC in 2005 to ~32 % in 2020.

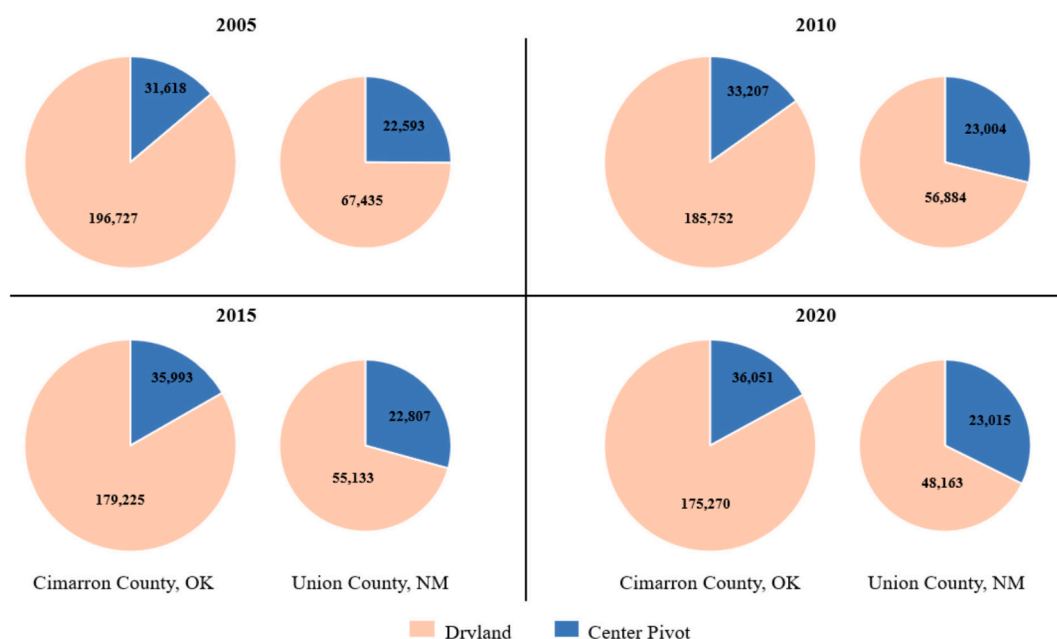


Fig. 3. Total area (ha) under cultivation by county, 2005 to 2020. Due to the relatively small area covered, other irrigation is not featured.

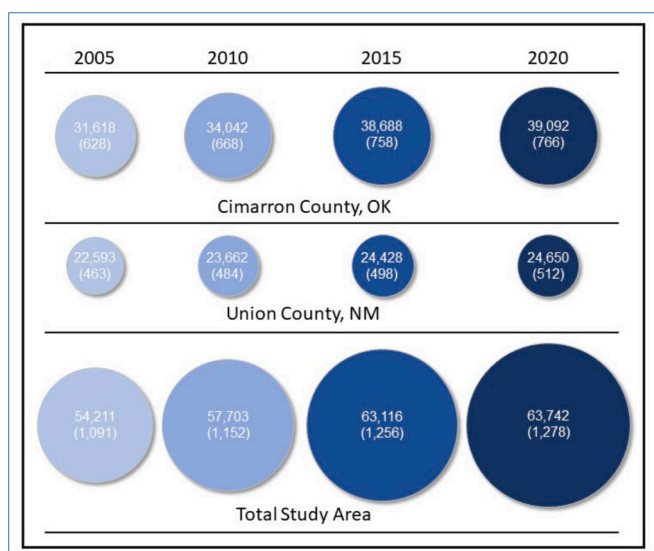


Fig. 4. Cumulative growth in area under center pivot irrigation and number of individual pivots (parenthesis). Circle size are proportional to the area covered.

4.3. Cumulative growth of CPI, 2005–2020

We explored cumulative growth of CPI due to long-term effects to both groundwater and soil resources (see Figs. 5 & 6). Results indicate that former traditional agricultural fields are often converted to irrigated agriculture and, therefore, remain under some form of cultivation (though some lands may be removed from cultivation and placed in the Conservation Reserve Program (CRP). Moreover, the growth of cultivated areas in the study area is largely attributed to the addition of irrigated fields.

Results show a steady increase in areas under CPI, both study area wide and within each of the two counties (Fig. 4). In 2005, ~54,211 ha of land was in CPI throughout the study area. By 2020, the total area of land impacted by CPI increased to 63,742 acres, a growth of 9531 ha (17.58 %) with an average growth rate of 5.6 % during the period of

investigation. The bulk of this growth (7474 ha) occurred in CC, which saw a growth from 31,618 ha in 2005 to 39,092 ha in 2020 (23.64 %) and an average growth rate of 7.45 % over the study period. UC, though, saw a slower growth, from 22,593 ha in 2005 to 24,650 ha in 2020 (9.1 %) and an average growth rate of 2.96 % over the study period.

4.4. Instability of CPI, 2005–2020

Though the study area showed a steady cumulative growth in CPI over the investigation period, our analysis indicates that the majority of the area under CPI (92.06 %) is stable, that is, once CPI came into production, the fields remained under CPI. However, ascertaining the number of pivots that remained stable is more difficult because an area under CPI can expand or contract, but the pivot or well, itself, remains stable. Moreover, fields can coalesce and, while the number of pivots may decrease, the actual area under CPI might increase. Conversely, fields can split and the number of pivots may increase, while the area under CPI associated with those fields may decrease. Nonetheless, despite this apparent stability, results reveal situations in which pivots are increasingly being temporarily or, in some cases, permanently taken out of service. For instance, a field may have been classified as CPI in both 2005 and 2015, but not in 2010 or 2020. Because our study period ends in 2020, we do not know if these wells were brought back into production and considered these to be conditionally unstable. While only about 1.5 % of the area under CPI is conditionally unstable, it nonetheless points to an emerging pattern occurring in the study. Lastly, ~6.52 % of the area under CPI was unstable, that is the pivots were only observed in 2005, 2010, or 2005 and 2010, but not in subsequent images.

Similar dynamics were present at the individual county level. Within CC, 91.8 % of the area classified as CPI was stable, 6.89 % was unstable, and 1.3 % was conditionally stable (Fig. 7). Similarly, within UC 92.48 % of the area classified as CPI was stable, with 5.92 % unstable and 1.6 % conditionally unstable (Fig. 8). The stability is not particularly surprising because installation of CPI systems can now cost upwards of \$130,000+ to install (see Irrigation Cost Calculator, 2025 <https://cropwatch.unl.edu/irricost>), though historically many of the households in the study area paid between \$35,000 and \$45,000 after subsidies, such as EQIP, for standard ~50 ha (125 ac) systems (USDA ARS

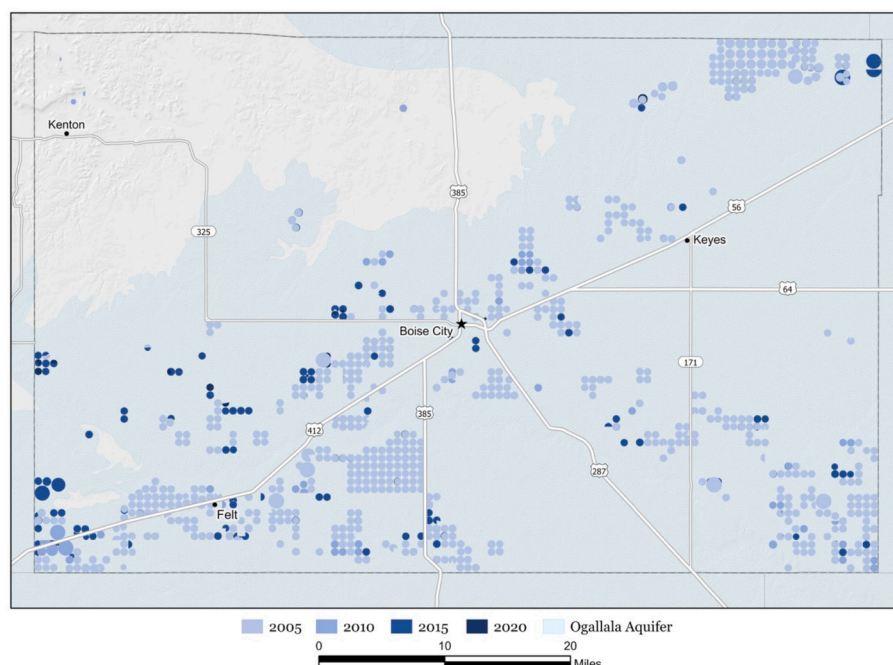


Fig. 5. Growth and spatial extent of center pivot agriculture in Cimarron County, OK (2005 to 2020).

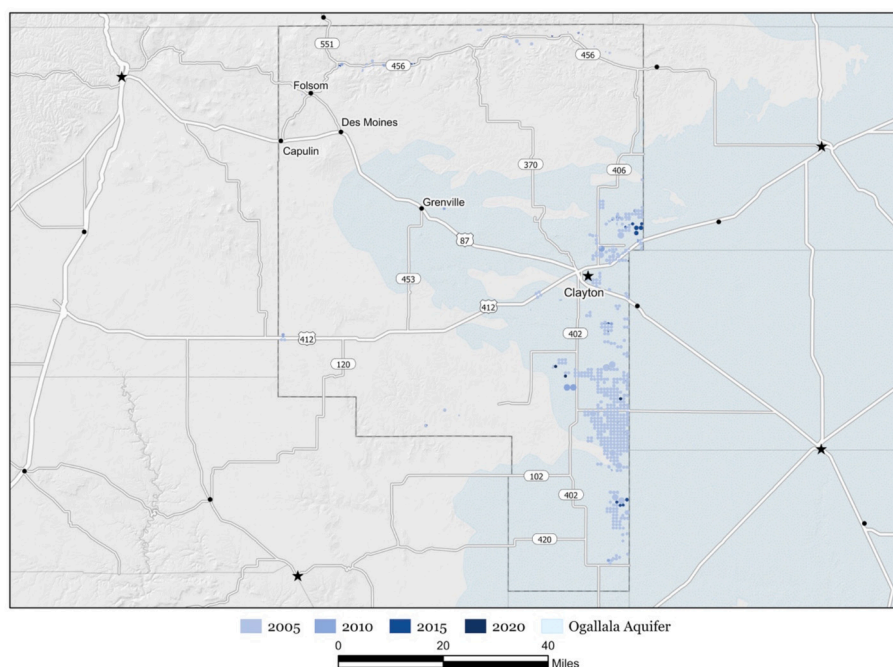


Fig. 6. Growth and spatial extent of center pivot agriculture in Union County, NM (2005 to 2020).

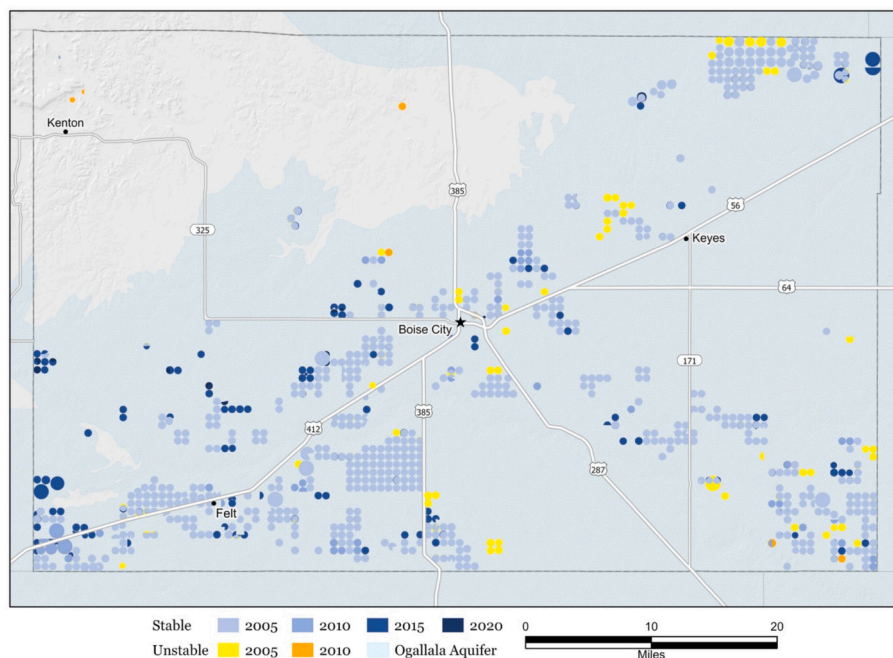


Fig. 7. Unstable CPI and spatial extent in Cimarron County, OK (2005 to 2020).

2001). However, the instability can be considered surprising given the costs of the technology installation. We better explain these trends, we explore the social dynamics of CPI next.

4.5. Perceptions regarding irrigation at the household level

Based on our household survey (Table 4, $n = 70$, Table 4), the majority of the households in the study area are involved in cattle ranching

(~91 %), while ~45 % of households grow crops, often in tandem with cattle raising. Of those growing crops, the majority of households also practice irrigation (~69 % of those who grow crops or ~31 % of all households in the study). More than 25 % of households indicate abandoning a well since 2018. The results from surveys indicate some ambiguity and a range of opinions regarding whether irrigation makes them less vulnerable (3.35/5, or slightly more positive than neutral, though not quite in agreement). However, households strongly agree

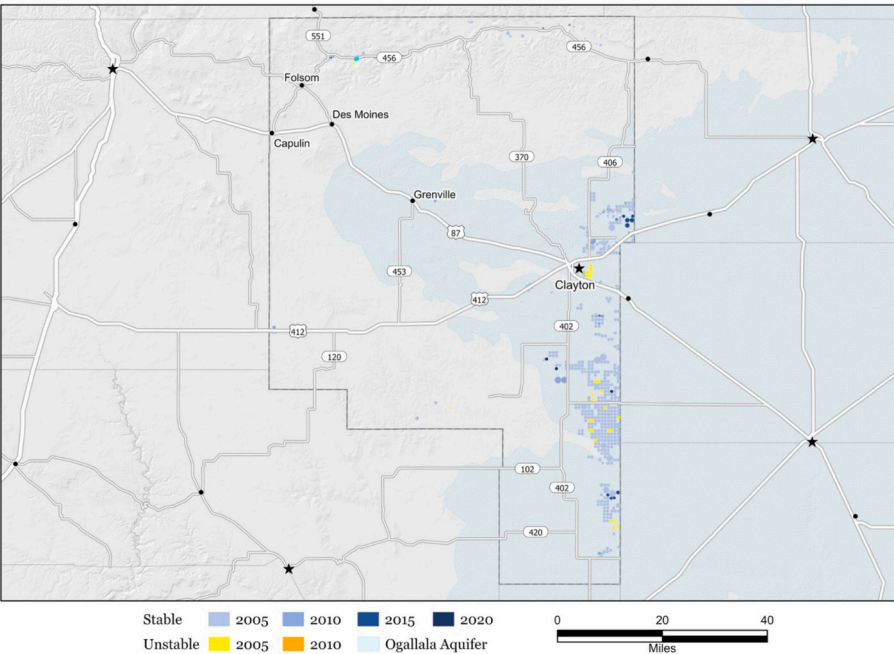


Fig. 8. Unstable CPI and spatial extent in Union County, OK (2005 to 2020).

Table 4
Study area 2022 household (HH) survey results: land use, water, CPI & perceived vulnerability (n = 70, (SD)) *(1 being strongly disagree, 3 neutral, 5 strongly agree).

	Average (SD)
HHs involved in Cattle (%)	0.91
HHs involved in Crop Production (%)	0.45
Total HHs Irrigating (%)	0.31
HHs abandoning wells (%)	0.27
Perceived Aquifer/Water Sustainability (years)	44.28 (40.15)
Perception Questions (Likert scale 1–5)*	
Irrigation makes me less vulnerable	3.35 (1.29)
There is enough water for irrigation	2.60 (1.09)
Water conservation is a concern	4.80 (0.50)

that water conservation is a concern (4.8/5), with most households perceiving aquifer sustainability to be less than 45 years (but note the bifurcation of opinion, SD). Further, households do not believe that there is enough water for irrigation (2.6/5). Overall, results suggest ambiguity in public perceptions of concern when it comes to irrigation, vulnerability, and water sustainability in the region.

4.6. Perceptions regarding irrigation at the community level

Overall, 6.4 % of respondents (n = 47, Table 5) perceived irrigation as reducing community vulnerability, while an additional 6.4 % remained neutral. Although irrigation was intended to make agriculturalists less vulnerable to drought, overall, irrigation appears to have the opposite effect. In fact, almost half of the key informants found

	Cimarron County, OK	Union County, NM	Total
Less Vulnerable	8.3 % (2)	4.4 % (1)	6.4 % (3)
Neutral	4.2 % (1)	8.7 % (2)	6.4 % (3)
More Vulnerable	54.2 % (13)	43.5 % (10)	48.9 % (23)
It's Complicated	33.3 % (8)	43.5 (10)	38.3 % (18)

irrigation made the community *more* vulnerable (48.8 %), while a large proportion perceived the relationship between irrigation and vulnerability as “complicated” (38.3 %).

4.6.1. Irrigation makes the community less vulnerable

Of the 6.4 % of those who noted that irrigation makes the community less vulnerable, informants stressed that irrigation was essential for their livelihood and economic sustainability. As one key informant noted, irrigation “makes people less vulnerable, because in this weather, dryland irrigation is complicated. Sprinklers help with efficiency, allows you not to waste any piece of land, and GPS technologies help a lot too.” Another saw irrigation as crucial to the sustainability of the region, noting that “irrigation stabilizes the economy.” There was also a general belief in technology, as CPI introduced after the little Dust Bowl of the 1950s, saved much of the community. These key informants held optimism that a new technology will “help us like it did before.”

4.6.2. Neutrality, irrigation, and community vulnerability

A few key informants took neutral positions in terms of their stance regarding the relationship between irrigation and vulnerability (6.4 %). The neutrality appeared to stem mainly from having a political position with a few key informants acknowledging the complex, controversial nature of continued irrigation to sustain and support agricultural livelihoods in the region in the face of cyclical drought, climate change, and aquifer drawdown, as well as the need to sustain and support agriculture and agricultural livelihoods in the region. Also, neutrality was perceived less politically and socially controversial rather than dealing with potential political fallout. In another instance, religious beliefs appeared to inform perceived neutrality,

Irrigation doesn’t make the community less vulnerable because nobody can control the drought. Not up to one person to open up [control] water, it means that they have control over the Lord, only the Lord ends the dry period.

In this sense, drought and conquering drought with the use of technology is beyond one’s control. As such, one needs to “let go” of that sense of mastery over nature.

4.6.3. Irrigation makes the community more vulnerable

By far, most key informants stated that irrigation makes their communities more vulnerable (48.9 %), conjuring a classic “Tragedy of the Commons” core logic (Hardin, 1968). Here, an “us versus them” rationale was used to understand the problem. Key informants noted the transboundary nature of water and difficulties with water governance across state lines, with many noting legal disputes. As one local leader explained, “there’s only one aquifer for many states of this country [‘country’ is often used colloquially to mean ‘land’], if it goes away, we have a problem.” Many key informants also noted the problems of outside corporations and/or greed, where only those with seemingly unlimited resources can keep irrigating,

Farmers who depend on rain are not vulnerable, but those who irrigate with groundwater are more vulnerable, if water tables drop in the aquifer. Corporations are the only ones with enough resources to keep drilling deeper wells and not being affected.

Here, dryland farmers are perceived as actually being less vulnerable than CPI irrigators because a dryland farmer can adjust and “see” what is going on in the natural environment. They are not dependent on a dwindling resource. In other words, the risk is known versus the uncertainty of seemingly invisible groundwater. Further perceptions of “us versus them” differences included perceived differences of farmers vs. ranchers, with ranching being perceived as the more “natural” land use suitable to the region. For farming, hay for local use by ranchers was acceptable but farming more water intensive crops was not.

This county was never intended to have as much irrigation as it does. Ranchers get affected, and they have to drill deeper wells...I know the water tables are already a visible issue, you can see it during drought time. We had four years of OK water, maybe mother nature will help again to replenish little by little.

Key-informants also expressed a perceived tipping point impacting long-term resilience,

You can only go so deep with wells to make a profit. Once there is not a profit, there is a point of no return. As soon as Texas sues New Mexico for the pecan irrigation using the Pecos River Valley, that production will stop. [I’m] Unsure if people can make decisions [to act] before reaching a point of no return. Looking back in history, the Dust Bowl happened because the environment reached a stop point. Looking at the tragedy of the commons, you know people will try to use the land as much as they can. Look at what is happening in Sedan [NM], where they are having the edge of that conversation on an ecologic stop point.

4.6.4. Irrigation, “It’s complicated.”

Similar to survey findings regarding the relationship between vulnerability and irrigation, a large proportion of key informants (38.3 %) expressed a “yes, it makes the community less vulnerable, but...” sentiment. As one key informant aptly stated, “It’s complicated.” “Buts” included concerns in the types of crops grown. For instance,

With or without the water situation, Union County [NM] should not grow any corn. This is the desert of the south. The production of gallons of ethanol is the basis of the farm bill...Mother nature and God did not intend for this land to grow corn. During a Soil and Water Conservation District meeting, a producer mentioned that they wanted to transform 800 acres of corn into hemp. Is it an opportunity? Is it based on water needs? Or both?... We’re fighting mother nature and not playing its way.

There were complex views on irrigation and how it impacted both urban and rural residents, with local leaders caught in the middle of needing to protect water sources for local cities and towns, but also wanting to support rural agriculturalists. As one key informant noted, “in the short term, irrigation makes farmers less vulnerable to drought, but not in a

long term. It is expensive to continue drilling water from an aquifer that is in decline.” The diminished aquifer affects urban and rural people equally, but much of the blame is placed squarely on the irrigators themselves,

The big thing on top of my mind is we need to be forced to put water meters on, and it needs to be enforced and stay within monitoring imposed limits. This is a serious matter, and nobody wants to run out of water. [We] need to think about what water represents for this place. No irrigated farming should be done here, we could have drinking water and live forever here, if we would have never started pumping for irrigation.

4.6.5. Perceptions and reality: the instability of CPI

Lastly, as the remote sensing analysis illustrates, irrigation, particularly CPI is becoming increasingly unstable both in reality and perception. Consequently, one of the “buts” is relative to both time and space (location). There is an increasing perception that while irrigation might make the community less vulnerable overall, there is only so much water left and that it is only a question of time before the source runs out. More importantly, the idea of water running out is much more nuanced over time and space. As one key informant explains,

The water tables are dropping down, and that’s a fact. When I was a kid, fifty years ago, there was a lot of land with water available. I remember a creek or *arroyo* by our ranch, and also several ponds of water [referring to rain fed ponds], but by 1990, you saw no more pools of water available, except when it rained. Through our place [referring to his current land/ranch] there’s a little creek that has never run dry, but I’m sure if we had any irrigation close by, it would be dry by now. That’s a common occurrence all over the county.

Key informants related the instability of CPI to what one is growing. Some crops (like corn) may require more wells (resulting in less visible crop circles), especially as water pressure drops, farmers often have no choice but to draw on more wells to grow crops on a single pivot. As a result, the CPI can appear unstable from year to year, although the associated water is still very much in use. Decisions on what crop to plant tends to be linked to market prices. For example, most farmers in the region will only convert to corn once the price rises above \$2.50USD a bushel, mainly because of growing costs, water usage, and perceived risks. As one key informant explained,

I’m not sure if there should be more restrictions or not, for sure, we need more strict rules for crop growing, people shouldn’t let their water [rules/resources] just be wide open, but when there’s less and less water underground, let’s say that you’re pumping 150 or 200 gallons per minute for the irrigation of just one section, then you end up using ten wells. Is it realistic and profitable for a farmer to do that? And how much does it affect the levels of the water table?

Even with irrigation, however, many farmers will still need to abandon water intensive crops (like corn), at the height of extreme drought conditions. Increasingly, CPI is seen as a tool among many that may or may not be appropriate depending on a variety of conditions such as precipitation, temperature, drought conditions, timing, location in relation to other wells/farms/crops, water pressure, crop type, as well as market and energy prices, to name a few. As one key informant noted,

Irrigation is good when used properly, but it’s hard to feel bad for farmers that rely heavily on central pivot irrigation since water was not here in the first place. Should we be raising these crops here? People talk about soybeans and cotton, adapt their crops to water scarcity. Less corn and more hay is necessary. The ones doing intensive crops are sometimes leasing land for watermelon, pumpkin, corn, which leads the land to destruction and death.

4.7. Synthesis via Triangulation of Results

The remote sensing analysis shows that the overall area under traditional dryland agriculture in the study region is decreasing, while a larger percentage of an operator's overall agricultural operation implements CPI. More recently, the amount of area in agriculture appears to be stabilizing, while CPI usage shows signs of instability or flux over time. Further, over the past decade indicates the rate of CPI growth has slowed, likely due to water insecurity, dropping water pressure, changing governance policies, extreme cyclical drought, climate change, external market forces, and increased education and public awareness.

Results suggest that Jevons' Paradox holds true for the lived experience of people and communities in the study area. Remote sensing results illustrate an increase in CPI across the study area while traditional agriculture and other irrigation techniques appear to fluctuate or even decline over time. The deployment of technologies to increase the efficient use of water suggests that water sustainability should be more achievable according to the logic of ecological modernization. However, survey respondent and key informant perceptions demonstrate the opposite. While ambiguity exists, quantitative analyses demonstrate that most respondents perceive their situation to be more precarious as a result of irrigation (irrespective of the adoption and growth of CPI technologies). These perceptions align with USGS data and other studies highlighting the diminishing aquifer (Scanlon et al., 2012), affirm climate models predicting increasingly extreme hazard events (such as more frequent, severe, and protracted drought), and the climate induced economic risk predicted for this region (Hsiang et al., 2017).

However, community stakeholder voices illustrate the tension between economic sustainability and environmental conservation of resources. Respondents discussed the necessity of continuing agricultural production despite the risks associated with current practices. The rationale for what crops to plant is largely based on market prices rather than sustainability. For example, electing to plant corn because of higher prices relative to other crops squarely situates the decision-making process on economic dimensions, ignoring the ecological repercussions (Gould et al., 2004). These decisions are further incentivized by policy incentives around ethanol subsidies in the USDA Farm Bill and the stipulations of crop insurance. Decision-making at the confluence of individual, economic, and policy factors aligns with the precepts of ecological modernization, suggesting that while technologies to "solve" this environmental problem do not yet exist, they have faith that human ingenuity and technological development in the future will ameliorate their current precarity. Environmental scholars attribute this mentality to the human exemptionalist paradigm—the conceptual separation of society from the influences of the natural world which refuses to acknowledge the latter's practical and material limitations (Catton and Dunlap, 1978; Foster, 2012). Moreover, some dissenters seemingly suggest an inclination toward the *intensification* of aquifer drawdown in light of a "tragedy of the commons" perception. Both real and perceived competition over a shared resource incentivizes more extraction, not less. Here, competition not only exists between family held farms in and across states, but also extends to the threat of industrial farming by large corporations. Such competition can also be categorized as acceptable (e.g. hay, wheat) vs. unacceptable (e.g. hemp, corn, biofuel) types of crops for the region. This competition also creates tensions between agriculturalists and rural cities and towns. Respondents implicitly and explicitly express frustration with what they perceive as unsustainable agricultural practices while exerting political and economic influence to gain more (spatially) and deeper (technologically) access to the Ogallala. These sentiments align with research demonstrating the tension between corporatization and family held farms relative LULCC and water scarcity in the southern high plains (Straub et al., 2025).

5. Scope and limitations

While the accuracy of our remote sensing analysis is high, it, alone, cannot tell us how much water is being used, the state of water pressure, or whether people need to combine pivot infrastructure due to crop type and/or degraded water resources. However, by looking at irrigation in more nuanced ways, raw, cumulative, and stable/unstable categories over time, we see a more robust picture of LULCC and water dynamics in the study area. Future analysis, in addition to incorporating ancillary data on aquifer drawdown, could benefit from the inclusion of additional CPI datasets from the region (e.g. Deines et al., 2019; Fagin et al., 2025; Hassani et al., 2021). Further, connecting "people to pixels" remains a challenge in this type of research. While the household surveys and key informant interviews were not randomly sampled, they were geographically stratified to ensure representation of diverse terrain and accompanying agricultural type and livelihood trajectories. Further, nesting scales across both household surveys and broader key informant interviews serves to triangulate the data. Taken together across space and time, the results show the complex dynamics between irrigation and perceived SES resilience and vulnerability. The sensitive nature of the data makes it difficult to get the big picture across a broad area. However, though imperfect, future research could focus on developing agent based models (ABMs) that incorporate demographics, crop type, estimated water usage, and community defined (co-produced) vulnerability indicators. Further, at a much smaller scale one can draw on well monitoring data to include in these dynamics. Overall, because water can make or break the property values in the region, it is difficult to (randomly) recruit households into such studies. At best, one can strive to triangulate this data in innovative ways.

6. Conclusions and policy implications

In the spirit of Jevons' Paradox, our study illustrates that technological intervention (CPI) appears to have the opposite effect of its original intentions. Objectively CPI is increasing in areas while at the same time, water levels in the aquifer is decreasing. Subjectively the majority of both households and larger community leaders report feeling that CPI makes them more vulnerable in the long run. At the same time, the results of the household survey and key-informant interviews illustrate a more nuanced view of this tension.

These findings call into question the efficacy of past and current policy and technocratic solutions designed to improve water sustainability in the region. At a federal level, we recommend increasing funding for research on drought resistant crops as alternatives to the more water intensive, but often financially lucrative, crops (e.g., hemp and corn). We also recommend changes to agricultural insurance that allow farmers to abandon watering crops they know have no chance of success, rather than being forced to continue consuming water on crops that are failing just to collect crop insurance. Second, we suggest addressing the corporatization of agriculture, which, given the trans-state nature and economically diversified structure of these companies, de-incentivizes conservation and sustainable resource use at local scales. At a state level, we believe an interstate compact, similar to the Red River Compact (1955), Republican River Compact (2004), and/or Great Lakes-St. Lawrence River Basin Water Resources Compact (2007), could be beneficial for the eight states that utilize the Ogallala Aquifer. Additionally, given the hydrogeology of the Ogallala with several subunits (Haacker et al., 2016), a subunit-based compact may be feasible. Such compacts would not only ensure each state has equitable access to the Ogallala, but it could also provide mechanisms to better measure and monitor groundwater use across the region. Additionally, standardized policies regarding groundwater rights across state lines could limit overexploitation by larger, out-of-state corporate entities. Lastly, states should also increase investment in extension programs that help integrate practical research and practice. These programs are (typically) well received and respected in rural spaces, overcoming

“outsider” fears well established in rural studies, in general, and in this region, specifically, and help cultivate social capital between rural spaces and government entities (Straub et al., 2025).

While our focus has been on a three state/three county region within the Ogallala Aquifer region, the issues experienced here are similar to issues faced elsewhere and involving other common resources. And while our focus is on the implications to state and federal policies, these issues are transnational and require input from multiple stakeholders.

Overall, an holistic and nuanced variation of Jevons’ Paradox is useful for understanding the historical relations between resource use, the mode of production, and the ecological implications of an ever expanding and increasing demand for resources, in this case, water. More studies are needed that intimately link LSS studies to biophysical processes directly related to water (i.e., geohydrology, etc.), engaging with water in tangible, material, and/or ecological ways. At the same time, such studies would benefit from the inclusion of theoretical and hydrosocial aspects of changing water resources, use, governance, and/or policy, etc. This is especially critical as ecological disorganization and environmental degradation are hastened by a litany of human-environmental stressors such as anthropogenic climate change coupled with changing global population and consumption patterns, and economies which necessitate an ever-increasing demand for water (Foster, 2009; Foster et al., 2010).

Declaration of competing interest

The authors declare no conflicts of interest. The sponsors had no role in the design, execution, interpretation, or writing of the study.

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Appendix A. GIS analysis overview

We quantified changes in agriculture using three separate approaches: overall (raw) change from year to year; cumulative growth of CPI; and stability of CPI once brought into production. All analysis were conducted in ArcGIS Pro 3.x using the center pivot GIS layers derived from remote sensing analysis and heads-up digitizing for 2005, 2010, 2015, and 2020.

A.1. Overall (raw) change

To quantify raw change, we generated summary statistics for each year under investigation, both at the county- (based on attributes in the GIS layer specifying the county) and study area-wide level. This entailed calculating the area of each digitized pivot using the Calculate Geometry tool in ArcGIS Pro. Once calculated, we summed the area of all pivots to determine the total area of CPI per year under investigation. We calculated changes in area by simply subtracting the previous years area

from the current years area ($y_2 - y_1$) and calculated percentage change using the following formula: $((y_2 - y_1) / y_1) * 100$. These calculations were performed outside of GIS software using Excel.

A.2. Cumulative CPI growth

Our digitization procedure involved identifying CPI (and other agriculture fields) in the earliest image year for each county and then heads-up digitizing each field. We then used the previous year’s features to inform the proceeding image years digitization. In this manner, we ensured that fields that did not change from year to year had the same geometry. Once we digitized the proceeding years fields, we used spatial analytical techniques (erase in ArcGIS Pro verbiage) to remove any fields present in the previous years GIS dataset from the current dataset, thereby creating a new GIS layer of only the newly added CPI fields. We repeated this process for all years under investigation. This enabled us to determine cumulative growth from y_1 to y_2 , y_2 to y_3 , and y_3 to y_4 .

A.3. Stable CPI classification

We created a typology to identify wells, that once brought into production, remained in production (stable wells) and those that came in and out of production based on 2005 and 2010 data (unstable wells). Because our digitizing methods ensured that each year’s CPI fields were built upon the previous year’s fields (though some fields coalesced into single larger fields or divided into smaller fields), we were able to use basic spatial analysis techniques (intersect in ArcGIS Pro verbiage) to ascertain the years each field were present. We classified fields that were identified as being present in all years under investigation (2005–2020) or consecutively after coming into production (e.g. 2010–2020; 2015–2020) as stable. Conversely, we classified fields only present in 2005, 2010, or only in 2005 and 2010, but not in subsequent years, as unstable. Lastly, there were situations in which fields were present in 2005 and 2015, but not in 2010 or 2020. Because our study ended in 2020, we do not know if these fields were brought back into production after 2020 and we, therefore, classified these as conditionally unstable.

Appendix B

B.1. Household survey questions

The following questions from the household survey were used in this paper:

Which of the following general types of commercial agriculture are you currently engaged in?

☐ _Cattle ranching ☐ _Other livestock production ☐ _Growing crops ☐ _Other (please specify).

Is the household operation involved in irrigated agriculture? ☐ _Yes ☐ _No.

Have you had to abandon any agricultural wells drilled on your property?? ☐ _Yes ☐ _No.

Explain (how many, when, why etc.).

How long do you think the current aquifer/water source used for agriculture will last (in years)?

(List any additional comments).

Answer the following opinion questions using the following 1–5 scale (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree). Please list any additional comments in the space below.

I feel that irrigation makes me less vulnerable. 1 2 3 4 5.

Water conservation is a concern to me. 1 2 3 4 5.

I have plenty of water available for irrigating crops. 1 2 3 4 5.

B.2. Key informant interview questions

This paper drew on one question from our Key Informant Interview guide:

In your opinion, does irrigation make the community more or less vulnerable to long-term drought? (Probe why or why not, how, etc.).

Data availability

Non-IRB protected data will be shared upon request.

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